

# INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



*This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:*

<https://www.issmge.org/publications/online-library>

*This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.*

## PRINCIPAL RESULTS AND BASIC METHODOLOGY OF THE CARACAS, VENEZUELA, SEISMIC MICROZONING PROJECT

Michael SCHMITZ<sup>1</sup>, Julio Javier HERNÁNDEZ<sup>2</sup> and the Caracas Seismic Microzoning Project Working Group.

### ABSTRACT

The principal results of the Caracas Seismic Microzoning Project consist of response spectra at different subsoil conditions within the sedimentary valley, and an estimation of landslide hazard for hillside areas. The methodology used for the development of the soil response comprises: probabilistic assessment of seismic hazard at rock sites; identification of soil and basin site effects; definition of microzones of similar seismic response. The seismic hazard in the area of Caracas was detailed with values ranging between 0.265 and 0.3 g for PGA and between 0.21 and 0.28 g for A1 (1-sec. period response), at four macrozones. We developed generic models of dynamic response using 1D equivalent linear analysis, considering variations in sediment thickness and  $V_{s,30}$ . The analytical results are calibrated and corrected by comparing them with actual earthquake response spectra; approximate 2D-3D basin effects are included. The distribution of microzones in the valley is based on geomorphologic, geological and geophysical modeling, and was calibrated by soil profiles from deep boreholes, and predominant periods from H/V. The earthquake triggered landslide hazard is evaluated using information regarding geology, geomorphology, geotechnical information, slope, weathering and anthropic alterations, by means of a modified Newmark method with Arias intensities. Thus, priority areas for intervention may be identified. Part of the study includes the evaluation of buildings regarding their typified structural reliability, calibrated with the 1967 Caracas earthquake damages, which will point out the priorities for retrofitting of existing buildings regarding their location within the different microzones.

Keywords: Microzoning, seismic hazard, site effects, response spectra, landslide, building retrofitting.

### INTRODUCTION

The Venezuelan capital Caracas is exposed to high seismic hazard due to its location on the limit between the Caribbean and South America plates, evidenced by La Tortuga, San Sebastián, Tacagua-El Ávila and La Victoria fault systems (from north to south; e.g. Beltrán, 1994; Audemard et al., 2000). The city with more than 3.5 million inhabitants is located in a tectonic valley 25 km long and 4 km wide, densely urbanized and extending today widely on the surrounding steep hills.

During its history, Caracas has suffered several destructive earthquakes, being the most recent one, the 1967 Caracas earthquake, a magnitude 6.6 earthquake which occurred as a multi-event earthquake between 25 northwest and 14 km north of Caracas (Suárez and Nábělek, 1990), which caused damage to numerous buildings, including the collapse of 4 multistory buildings (e.g. Briceño et al., 1978), with more than 300 people killed. Damage investigations of buildings were performed in detail, including soil and

<sup>1</sup> Head of Geophysics Department, FUNVISIS, Final calle Mara, Urb. El Llanito, Caracas, Venezuela, e-mail: [mschmitz@funvisis.gob.ve](mailto:mschmitz@funvisis.gob.ve)

<sup>2</sup> Consultant in Earthquake Engineering, Caracas, Venezuela, e-mail: [julher@cantv.net](mailto:julher@cantv.net).

building dynamical characteristics, and the earthquake engineering characteristics of the deposits, seen as the fundamental factor for earthquake damage (e.g. Whitman, 1969; Seed et al., 1970; Arcia et al., 1978). The particular behavior of the thick soil deposits in the east of Caracas valley had attracted attention during the past decades, leading to detailed studies of seismic response and ground shaking characteristics (e.g. Papageorgiou and Kim, 1991; Abeki et al., 1998; Semblat et al., 2002; Rocabado et al., 2006). The seismic building code (COVENIN, 2001) does not consider important parameters like the sedimentary thickness to basement and basin geometry, but the thickness of strata up to the engineering rock with  $V_s > 500$  m/s.

During “Basic Study on Disaster Prevention” (Yamazaki et al., 2005), various scenarios for earthquake disaster were studied. Nevertheless, basin effects as observed during the Caracas 1967 earthquake, could not be modeled thoroughly, and the need for more complete subsurface studies was evidenced. This task, which had been started previously (Schmitz et al., 2002) was done with financial support of the program FONACIT- BID II 200400738 within the scope of the Caracas and Barquisimeto seismic microzoning study in the years 2005-2009. The principal objective of this study was the identification of zones of similar response to seismic motion, in order to be able to adjust seismic design of buildings to the different scenarios within the city, considering the integration of geological, geophysical, geotechnical and seismological information for the definition of microzones in an interdisciplinary approach (Hernández et al., 2006). We present the fundamentals of the methodology applied, as well as the principal results of subsurface evaluation and microzones with the design spectra derived for each of them.

A fast growing part of the city with more than half of its population comprises informal housing at steep hillsides surrounding the valley with earthquake or rainfall triggered landslide as the principal hazard in these areas. Therefore, a methodology for the evaluation of the susceptibility to mass movements, including local calibrations, was applied (Hernández et al., 2008). We consider crucial the concise development of local building regulations, which take into account the results presented here with a diversity of scenarios, which may contribute to the mitigation of the seismic risk in Caracas by means of land use planning, retrofitting of existing buildings and design of new constructions according to the seismic response expected for each microzone.

## **METHODOLOGY**

The estimation of the soil motion in different areas of a city is an efficient tool for mitigation of seismic risk, being site amplifications crucial for local behavior (Bard, 1999). We present a resume of the methodology applied in this study, exposed in detail in Hernández et al. (2006), which is aimed at the definition of the level of seismic hazard and the possible local effects.

The principal elements used within the study are:

- 1) Characterization of the sources: historic seismicity, neotectonic analysis, paleoseismology, and seismological studies.
- 2) Probabilistic evaluation of seismic hazard at outcropping rock and their variation within the study area in north-south direction, considered for the amplitude of the typified response spectra.
- 3) 1-D parametric study of the dynamic response using a linear equivalent analysis (Schnabel et al., 1972), for varying sediment thickness (between 10 and 350 m) and average shear wave velocity for the upper 30 m ( $V_{s,30}$  between 150 and 650 m/s), grouped within 12 classes (Table 1) according to their typical behavior. The results are calibrated and corrected by means of comparison to spectra from earthquake records (PEER, 2005).

- 4) Spatial site effects: incorporation of 2-D and 3-D basin effects and topographic effects.
- 5) Definition of microzones of similar seismic response according to geomorphologic, geological and geophysical data of the sedimentary basin fill and geotechnical properties of the rocks exposed at hillsides, topographic analysis and the detailed evaluation of building damage due to the 1967 Caracas earthquake.
- 6) Outside the sedimentary areas, the earthquake triggered landslide hazard is evaluated using information regarding geology, geomorphology, inclination, weathering and anthropic modifications. Thus, priority areas for intervention may be identified.
- 7) Part of the study comprises the evaluation of existing buildings regarding their typified structural behavior, leading to the priorities for intervention regarding their location within the different microzones.

All the information generated within the project is introduced in a Geographic Information System (GIS), which will enable the interaction with local institutions and urban planners for fast implementation of the recommendations. Interaction with local communities is organized by the “Aula Sísmica Madeleilis Guzmán” at FUNVISIS, a unit that works in disaster prevention education.

**Table 1. Groups of generic soil profiles used for dynamic response of sediments and resulting microzones associated; (n = 1, 2, 3 or 7).**

H, deposit (m)	V <sub>S,30</sub> (m/s)		
	≤ 185	185 - 325	> 325
< 60	GP-01 / 3-3	GP-02 / n-2	GP-03 / n-1
60 - 120	GP-04 / no	GP-05 / 4-2	GP-06 / 4-1
120 - 220	GP-07 / no	GP-08 / 5	GP-09 / 5
> 220	GP-10 / no	GP-11 / 6	GP-12 / 6

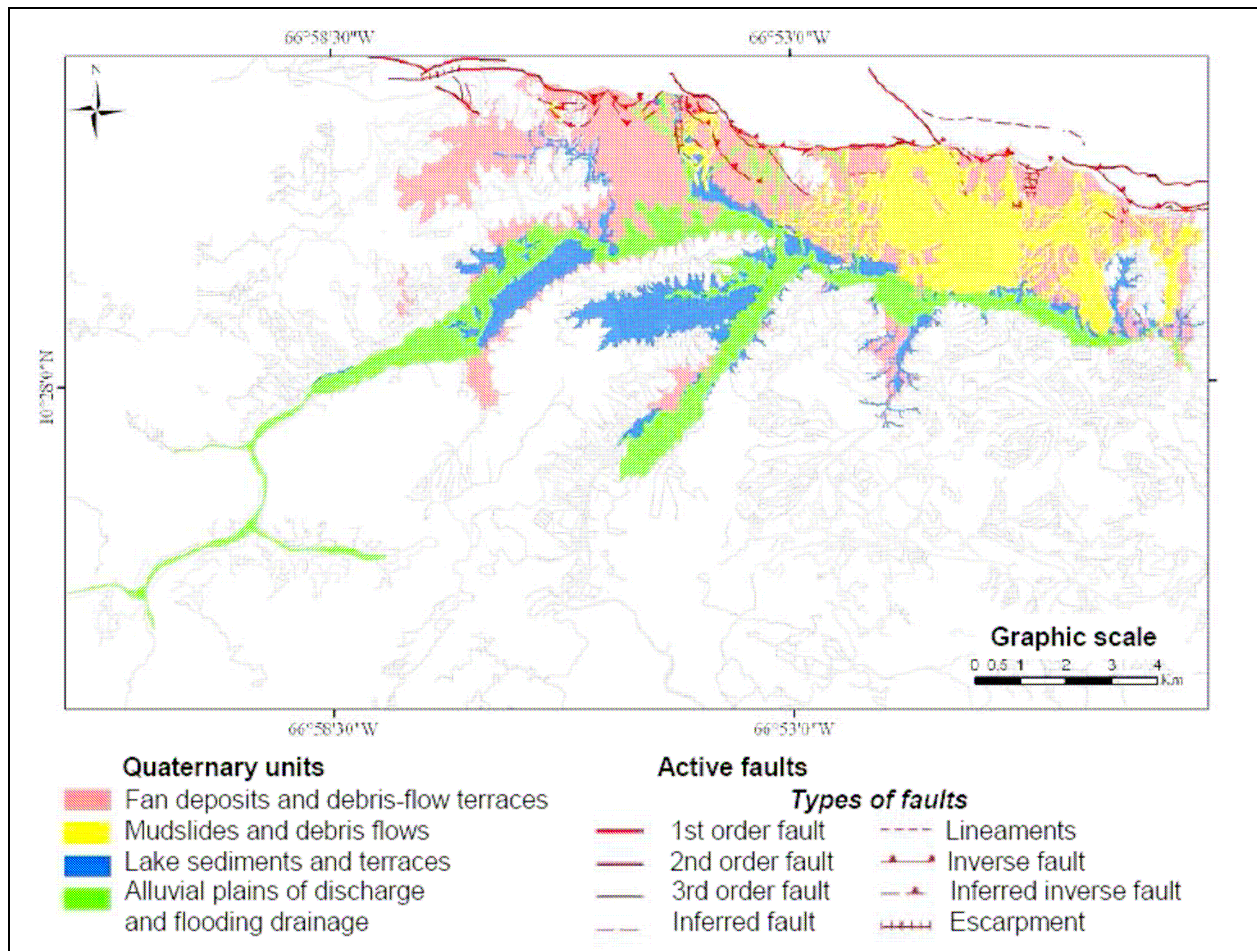
## PRINCIPAL RESULTS

### Subsurface model of the Caracas valley

The information regarding the subsurface model of the Caracas valley, crucial for the determination of the seismic response within Caracas Metropolitan Region, was obtained by means of the interaction of different disciplines within the working group, and was integrated in the map of microzones, containing the principal characteristics together with recommendations for their application. We concentrated on the relation between geology, the geophysical characteristics of the deposits and the dynamic response they might generate, in order to associate typified spectra to each microzone.

The mapping of the principal geological formations and geomorphologic units, together with the information on sedimentary thickness and seismic velocities of the near surface units, constitutes the basic information for the definition of microzone boundaries. The principal bedrock units that compose the base of the sedimentary valley are the Las Brisas and the Las Mercedes schists, the same units that are cropping out in the hills south of the valley. Additionally to the geological mapping (Urbani and Rodríguez, 2004), an analysis of the distribution of the quaternary sediments (Singer et al., 2007; figure 1) enables us to define their limits with regard to the bedrock and the internal sedimentary structure within the valley. The determination of sedimentary thickness bases on the data from drillings aimed for groundwater exploration (Delaware, 1950; Kantak et al., 2005), seismic refraction profiles (Murphy et al., 1969; Sánchez et al., 2005), depth estimates from the conversion of predominant periods from more than 1500 individual sites of ambient noise measurements, to which the H/V analysis (Bard, 1999) was applied (Rocabado et al., 2006; 2010), and 3-D gravimetric modeling (Amarís et al., 2011). 4 deep drillings (110

to 280 m in depth), done within the scope of this project, allow for the calibration of the sedimentary thickness, which were corrected specifically in the northeastern (Los Chorros) and western (San Bernardino) part of the valley, where information from previous investigations pointed to a thickness in the order of 100-120 m, whereas the new drillings allowed to derive a thickness of more than 200 m in both cases (see Amarís et al., 2011). At two sites (La Carlota and San Bernardino) the geotechnical profile was derived down to bedrock. At the three sites in the western part of the valley, strong motion observatories were installed with three component sensors at three different depth ranges (at bedrock, 30 m depth and the surface). In the future, the records from these observatories will be used for the calibration of the geophysical and geotechnical model. Areas with predominant periods superior to 1 s coincide with sediment thickness of more than 100-150 m (Rocabado et al., 2010). The information on the predominant periods is also used for the calibration of the microzone boundaries.



**Figure 1. Simplified Quaternary geological units of Caracas valley (Singer et al., 2007).**

One of the critical parameters for the characterization of the subsoil is the shear wave velocity, indicated in the Venezuelan building code (COVENIN, 2001) as the fundamental parameter for determination of the respective spectral form. For practical purpose, we decided to use the shear wave velocity of the upper 30 m ( $V_{s,30}$ ), as is used in different seismic building codes (e.g. BSSC, 2003, CEN, 2003), as one of the parameters for the parametric 1-D study of dynamic response. The distribution of  $V_{s,30}$  is based on the Standard Penetration Test (SPT) indexes from geotechnical drillings at about 1,000 sites (Feliziani et al., 2004), that have been converted to shear wave velocities using empirical conversion formula for

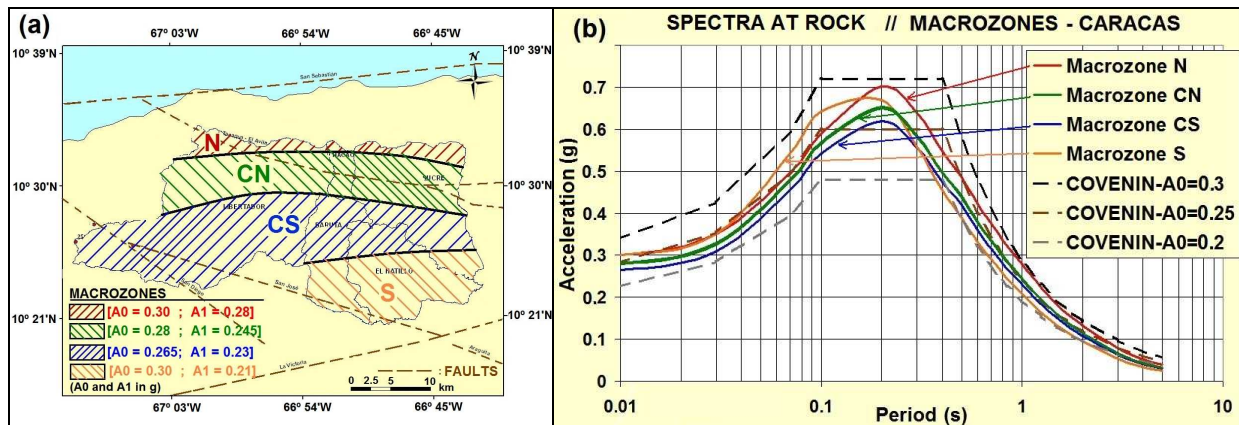


sedimentary deposits (Imai and Yoshimura, 1970; Ohta and Goto, 1978). The values obtained have been compared and integrated with direct observations of seismic refraction measurements (Campos et al., 2004; Morales et al., 2008), spectral analysis of surface waves (SASW) (García et al., 2006), microtremor array measurements (Cornou et al., 2010), and downhole and crosshole measurements (Murphy et al., 1969; Campos et al., 2004). Outside the sedimentary valley,  $V_{s,30}$  has been estimated using a methodology proposed by Wald and Allen (2007) and Allen and Wald (2009), using a map of slope inclination from SRTM-data (Morales et al., 2010).

### Seismic Hazard

Following the Venezuelan building code (COVENIN, 2001), the PGA at rock outcrop is 0.3 g for a mean return period of 475 years, based on regional intensity attenuation laws with few details in the near field. For the Caracas seismic microzoning project, a probabilistic seismic hazard assessment was performed, applying a revised seismogenic model (Hernández, 2009a), worldwide attenuation laws of spectral response at different vibration periods, and including fault rupture directivity effects (Abrahamson, 2000), aiming to obtain uniform hazard spectra at rock outcrop. The uniform hazard spectra are characterized by PGA ( $A_0$ ) and by the elastic response of structures with a period of  $T = 1$  s ( $A_1$ ).  $A_0$  shows the highest values of 0.3 g to the north and south, due to the vicinity to the faults, whereas  $A_1$  decreases from north to south (Hernández and Schmitz, 2009), as it depends basically on the high seismic magnitudes that are feasible for the more active faults to the north.

The resulting hazard was grouped in 4 macrozones with representative values  $\{A_0; A_1\}$  and the definition of elastic spectra (damping  $\xi = 5\%$ ) at rock outcrop (Figure 2).  $A_0$  varies between 0.265 g in the center and 0.3 g to the north and south, whereas  $A_1$  decreases from 0.28 g in the north to 0.21 g in the south of Caracas (Hernández and Schmitz, 2009); the respective spectra are below the ones of the building code.



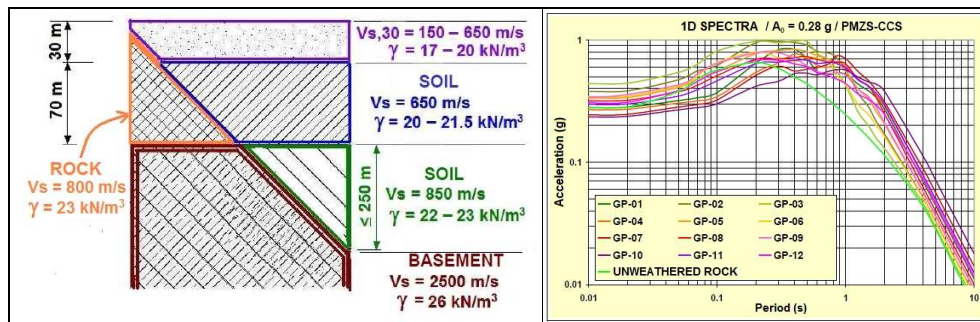
**Figure 2. Macrozones of seismic hazard for Caracas Metropolitan Region (left: N = north; CN = center-north; CS = center-south; S = south), and uniform hazard elastic spectra ( $\xi = 5\%$ ) at rock outcrop for each macrozone compared to the building code spectra (Hernández and Schmitz, 2009).**

### Response spectra

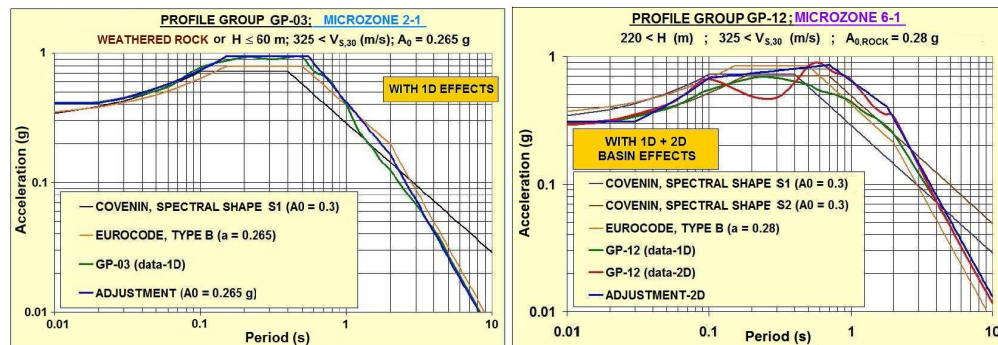
In order to assign response spectra for each microzone, generic models of dynamic response were created, exploring the variations in terms of shear wave velocity ( $V_{s,30}$ ), with values distributed in 9 classes (between 150 and 650 m/s), and varying sediment thickness (between 30 and 350 m thickness), including some additional cases with 10 and 20 m thickness for a total of 103 different soil profiles (Hernández et al., 2010). Geotechnical information was derived from deep drillings and available geotechnical

information, in order to define a scheme with basic geophysical (shear wave velocities after Sánchez et al., 2005) and geotechnical parameters (Figure 3, left), with the generic variations indicated above.

To each soil layer 2 sets of curves of non-linear behavior, considering the extreme cases of fine and granular material, were assigned and a linear equivalent analysis (Schnabel et al., 1972) of the 1-D site response was done. Seismic motion input was defined from six strong motion records -representative of the seismic hazard at rock outcrop- deconvolved to bedrock. The derived elastic response spectra ( $\xi = 5\%$ ) were grouped into 12 classes with 1-D spectra weighted for each of them (Figure 3, right) within the limits displayed in table 1. Then, they were compared with spectra from actual records for earthquakes of similar intensity in similar sites (PEER, 2005), needing few small corrections that point out to a good reliability of the methodology. For the final response spectra, 2-D and 3-D basin effects are taken into account, as they have been a key factor for damage distribution during the 1967 Caracas earthquake. Using the spectra derived by Papageorgiou and Kim (1991) for Los Palos Grandes area, response spectra which include 2-D effects were derived for each microzone modifying the 1-D spectra, with amplifications in the period range up to 2 s, and with an extended period range up to 4 s based on a 3-D model of seismic response (Delavaud, 2007). Examples of the derived response spectra including 2-D and 3-D basin effects are displayed in figure 4 for weathered rock (left) and for the deepest part of the sedimentary basin (right).



**Figure 3. Scheme of shear wave velocities and unit weight for the geophysical / geotechnical model used for parametric study of 1-D dynamic response (left) and 1-D elastic response spectra ( $\xi = 5\%$ ) for site classes for a PGA of 0.28 g corresponding to most of the sedimentary valley (right).**



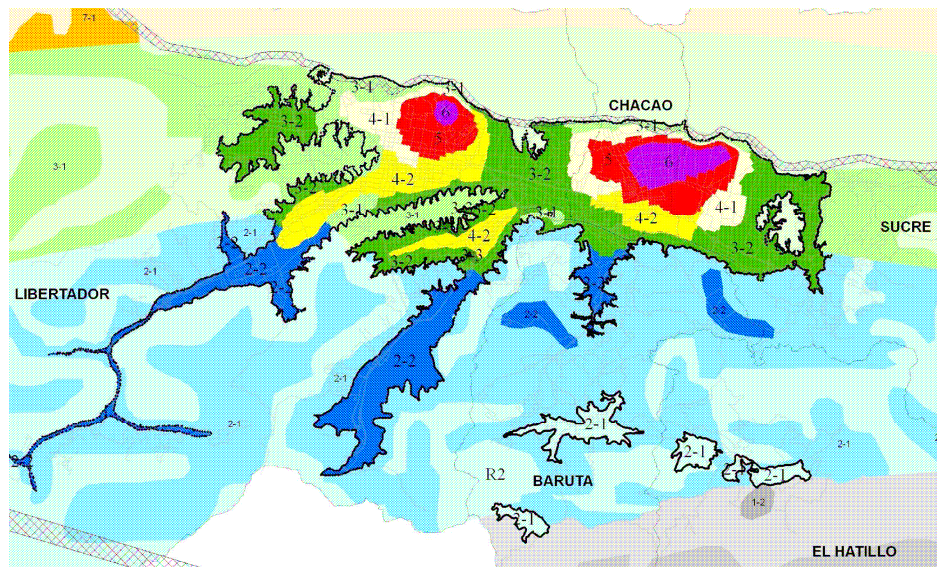
**Figure 4. Elastic response ( $\xi = 5\%$ ) spectra for microzones with weathered rock (left) and a sediment thickness of more than 220 m (right), both examples for  $V_{s,30} > 325$  m/s (Hernández et al., 2010).**

The response spectra for each group are compared with the building code spectra from the Venezuelan code (COVENIN, 2001), showing several important differences. Additionally, comparisons to the spectra

of the EUROCODE 8 (CEN, 2003) and those derived within the seismic microzoning project for Thessaloniki, Greece (Pitilakis, 2004) were done. We obtained a good fit with the modern spectra from these documents, pointing to a good reliability of the applied methodology. The response spectra for rigid and intermediate stiff soils are higher than the ones of the local code (COVENIN, 2001) in the period range 0.5 to 2 s (Figure 4). Nevertheless, the spectra at unweathered rock are less demanding than the code spectra. In the future, calibrations will be done with the experimental transfer functions from observations of the strong motion observatories. Estimates for topographic effects were introduced, following the French recommendations (AFPS, 1990) for different situations at hillsides, which are responsible for short period amplifications.

### Definition of microzone boundaries

For the definition of the boundaries between microzones, that take into account the modifications of seismic motion due to the sediments and rock weathering, the map of Quaternary geological units (Figure 1), the sedimentary thickness grouped into 4 classes (Amarís et al., 2011), the distribution of  $V_{s,30}$  (Morales et al., 2010), the damage distribution after the 1967 Caracas earthquake (Briceño et al., 1978), the distribution of 3-D basin effects (Delavaud, 2007) and the macrozones from the seismic hazard assessment (Hernández and Schmitz, 2009) are taken into account. The final map of microzones is displayed in figure 5; for each individual microzone a response spectrum is assigned. For the microzones 4 – 6, all located within the sedimentary valley and with a sediment depth of more than 60 m, 2-D and 3-D basin effects are incorporated in the spectra. The distribution of the microzones was calibrated by different means, as for example the modeling of geotechnical profiles down to bedrock and predominant periods from ambient noise measurements and empirical transfer functions. Data from three deep (110 to 280 m depth) accelerographic observatories will help to constrain the results in the future. In the vicinity of the active faults (Tacagua and El Ávila in the north with minor uncertainty; Sur Guarenas in the east and San Antonio and San José in the south with greater uncertainty), a security corridor is marked as suggested by Bryant and Hart (2004), in order to account for permanent deformations. At hillsides, the level of weathering of the rocks is taken into account by means of the  $V_{s,30}$  in order to assign design spectra for hard rock or weathered rock, as well as for topographic effects.



**Figure 5. Zoning of seismic hazard at rock outcrop and microzones of similar seismic behavior for the Caracas valley. Variations of  $A0/A1$  for macrozones and the corresponding spectra at rock, R7: 0.3/0.28 g; R3 (including microzones 3-6): 0.28/0.245 g; R2: 0.265/0.23g; R1: 0.3/0.21 g. Variations of sediment thickness and  $V_{s,30}$  define the spectra: sediments of 0 to 60 m: 1-1, 2-1, 3-1, 7-1 ( $V_{s,30} >$**



325 m/s), 1-2, 2-2, 3-2 ( $V_{S,30} = 185\text{-}325$  m/s) and 3-3 ( $V_{S,30} < 185$  m/s); sediments of 60 to 120 m: 4-1 ( $V_{S,30} > 325$  m/s) and 4-2 ( $V_{S,30} = 185\text{-}325$  m/s); sediments of 120 to 220 m: 5 ( $V_{S,30} > 185$  m/s); sediments greater than 220 m: 6 ( $V_{S,30} > 185$  m/s); see table 1 for overview of spectra.

### Earthquake triggered landslide hazard

Outside the sedimentary valley, the slope stability was analyzed at a scale 1:25,000 with respect to the landslide hazard triggered by earthquakes (Hernández et al., 2008). Six hazard levels were identified (Figure 6) which is aimed to help decision making to assign priority for more detailed studies and the implementation of mitigation measures. The study was based on geological, geomorphologic and geotechnical information derived previously in the central part at a scale 1:10,000 (Feliziani et al., 1985), as well as digital elevation models. A geotechnical characterization of the hillsides was done, taking into account the lithological characteristics and structure, the slope inclination and extern geodynamics (geomorphology and land use). The obtained maps of geotechnical orientation and susceptibility to plain slides were calibrated in the Alto Prado neighborhood at a scale 1:2,500, and they were correlated with historic and recent landslides triggered by rainfall. For the evaluation of the earthquake triggered landslide hazard a methodology using Newmark (1965) displacements, which had been calibrated in areas with earthquake induced landslides, was applied, taking into account seismic hazard by Arias intensities for a mean return period of 700 years, corresponding to building code specifications for large-scale buildings.

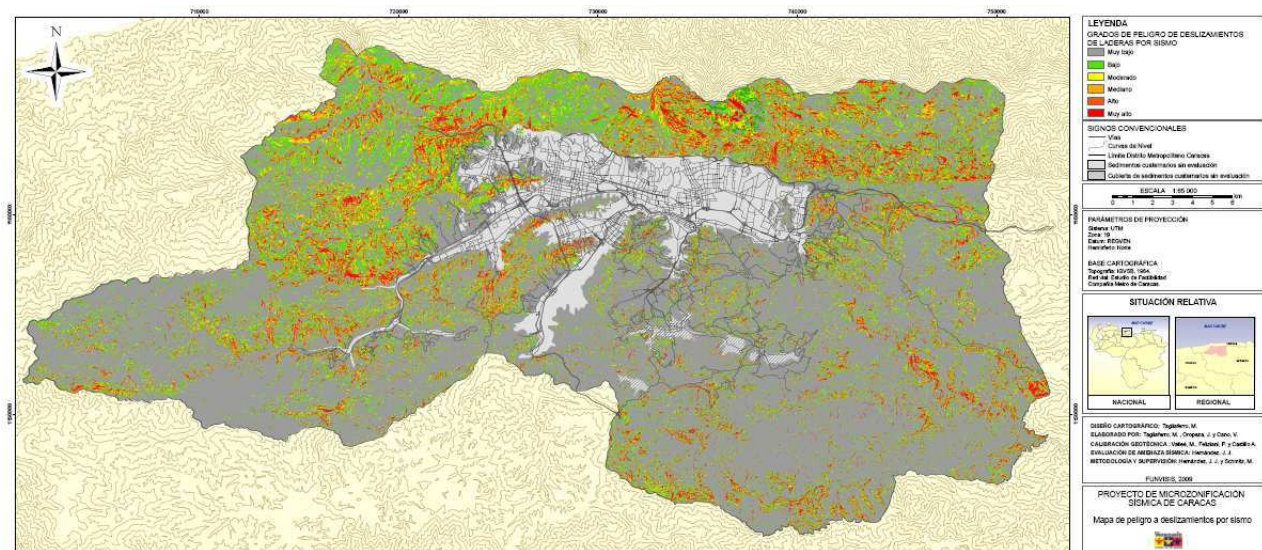


Figure 6. Map of earthquake triggered landslide hazard for hillside areas in Caracas (Hernández et al., 2008).

### Structural reliability

In order to establish recommendations for retrofitting the riskier buildings of the city according to their microzone location, an approximate evaluation of typical buildings was performed. For 13 construction practices (combinations of 9 seismic codes and 7 concrete design codes) employed between 1939 and 2009, and for buildings of 1 to 20 stories, we estimate their design inelastic spectra and compare with the demand inelastic spectra in 8 microzones, including several detailed evaluations. This set was divided into groups of two thicknesses of deposits (more and less than 120 m), and three building heights (low, medium and tall). Building responses were analyzed by means of the modern structural reliability theory relating ductility demands with several damage levels (moderate, severe and total), calibrated with the 1967 Caracas earthquake damages (Arcia et al., 1978). Fragility curves (see Figure 7 for severe damage of

medium height buildings on the thicker deposits) and reliability indexes for those damage levels, loss estimates for several seismic scenarios and expected total losses were obtained (Hernández, 2009b). All of these results support advices of priorities of seismic building upgrading, being their construction practice the more influential factor.

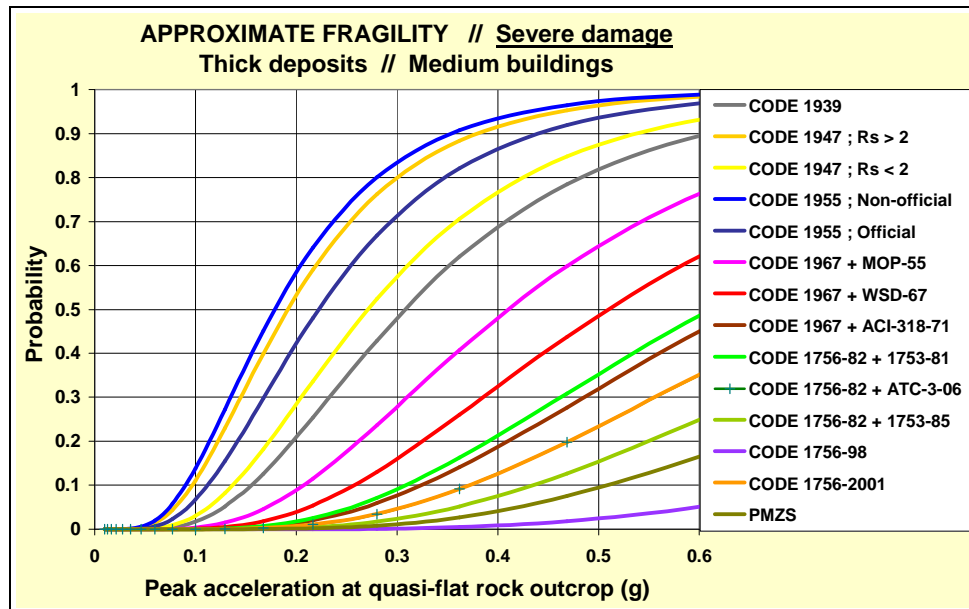


Figure 7. Fragility curves for severe damage of medium height buildings in thick deposits (Hernández, 2009b)

## CONCLUSIONS

During the 1967 Caracas earthquake, the damage distribution evidenced strong site effects within the sedimentary valley. Nevertheless, the principal parameters which control the seismic response, as sediment thickness of more than 50 m and basin geometry, are not considered in the Venezuelan building code (COVENIN, 2001), motivation for the realization of the Caracas seismic microzoning study. A multidisciplinary approach for the evaluation of the seismic response was applied with the generation of generic subsoil models depending on the thickness of the sediments and the shear wave-velocity for the upper 30 m ( $V_{s,30}$ ), considering a fixed model of geophysical and geotechnical characteristics of the valley sediments. The obtained spectra were calibrated by comparing with representative earthquakes records, and basin effects were introduced for sediment depths greater than 60 m. The results of this project allow to assign reliable response spectra for the different parts of Caracas. An evaluation of earthquake triggered landslide is also included in the project, based on the evaluation of the landslide susceptibility and earthquake triggered landslide potential considering seismic hazard by Arias intensities. The resulting maps may be used for the definition of areas for most urgent intervention and reference for more detailed technical studies. In order to define priorities for upgrading of the existing building stock, a vulnerability evaluation of typified buildings regarding their age of construction, height and location with regards to the sedimentary thickness was done, which allows to focus on the most urgent types for evaluation and retrofitting. An efficient elaboration of recommendations and local building codes will be of paramount importance for the implementation of the project results, in complement to the national building code, which allows for special projects to substitute locally the national regulations.

---

ACKNOWLEDGEMENTS

Further members of the Caracas Seismic Microzoning Project Working Group are: A. Aguilar, I. Aguilar, L. Alvarado, F. Anzola, J. Araque, F. Audemard, J. Azuaje, P.Y. Bard, H. Cadet, V. Cano, E. Caraballo, A. Castillo, L. Colmenárez, C. Cornou, E. Delavaud, J. Domínguez, P. Feliziani, Y. Flores, K. García, J. González, M. González, J. Guzmán, A. Hernández, A. Justiniano, V. Leal, R. López, W. Marín, D. Molina, J. Moncada, C. Morales, R. Ollarves, J. Oropeza, M. Palma, M. Paolini, B. Quintero, H. Rendón, V. Rocabado, J. Rodríguez, L. Rodríguez, G. Romero, J. Sánchez, A. Singer, M. Tagliaferro, F. Urbani, R. Vásquez, M. Vallée, M. Villar, J.-P. Vilotte, A. Zambrano, H. Zambrano, J. Zamora. Funding was provided by the “Proyecto de Microzonificación Sísmica en las Ciudades Caracas y Barquisimeto” (FONACIT – BID II 2004000738).

REFERENCES

- Abeki N., Seo K., Matsuda I., Enomoto T., Watanabe D., Schmitz M., Rendón H. and Sánchez A. (1998). Microtremor observations in Caracas city, Venezuela. In: Irikura et al., (ed.). The Effects of Surface Geology on Seismic Motion, Rotterdam, AA Balkema, pp. 619-624.
- Abrahamson, N. (2000). Effects of rupture directivity on probabilistic seismic hazard analysis. 6th Int. Conference on Seismic Zonation, 2000, Palm Springs, California.
- AFPS (1990). Recommendations of the French Association for Earthquake Engineering for the redaction of rules relative to structures and installations built in regions prone to earthquakes. Association Française du Génie Parasismique, Saint-Rémy-lès-Chevreuse, France.
- Allen, T. and Wald, D. (2009). On the use of high-resolution topographic data as proxy for seismic site conditions (Vs30). Bulletin of Seismological Society of America, Vol. 99, No. 2A, pp. 935-943.
- Amarís, E., Schmitz, M. and Murphy, V., 2011. Sediment thickness as primary input for the Caracas Seismic Microzoning Project. 5th International Conference on Earthquake Geotechnical Engineering, Santiago de Chile, January 10-13, 2011, submitted.
- Arcia, J., Briceño E. and Schmidt, L. (1978). Evaluación e interpretación de daños. Chapter X in Segunda fase del estudio del sismo ocurrido en Caracas el 29 de julio de 1967, Comisión Presidencial para el Estudio del Sismo, Ministerio de Obras Públicas. FUNVISIS [editor]. Caracas.
- Audemard, F.A., Machette, M., Cox, J., Dart, R. and Haller, K. (2000). Map and Database of Quaternary Faults in Venezuela and its Offshore Regions. US Geological Survey, Open-File Report 00-0018. Include map at scale 1:2,000,000 and 78-page report.
- Bard, P.Y. (1999). Microtremor measurements: a tool for site effect estimation? In: Irikura, K., Kudo, K., Okada, H. and Sasatani, T. (eds.), The Effects of Surface Geology on Seismic Motion - Recent progress and new Horizon on ESG Study, Vol. 3, Balkema, Rotterdam, pp. 1251-1279.
- Beltrán, C. (1994). Trazas activas y síntesis neotectónica de Venezuela a escala 1:2.000.000. VII Congreso Venezolano de Geofísica, Caracas, pp. 541-547.
- Briceño, F. and 48 co-authors (1978). Segunda fase del estudio del sismo ocurrido en Caracas el 29 de julio de 1967. Comisión Presidencial para el Estudio del Sismo, Ministerio de Obras Públicas, 2 volumes, 1281 pp. [FUNVISIS, editor, Caracas].
- Bryant, W.Y. and Hart, E. (2004). Fault-Rupture Hazard Zones in California. Alquist-Priolo Earthquake Fault Zoning Act with Index to Earthquake Fault Zones Maps. California Department of Conservation. California Geological Survey. Special Publication 42, 46 pp.
- BSSC (2003). NEHRP recommended provisions for seismic regulations for new buildings and other structures (FEMA 450). Building Seismic Safety Council (BSSC), NIBS, Washington.

- Campos, A., Schmitz, M. and Cataldi, A. (2004). Definición de las relaciones entre parámetros geofísicos y geotécnicos en pozos disponibles a lo largo de la línea 4 del Metro de Caracas. XVIII Seminario de Geotecnia, Caracas, 2004, Reports in CD, 12 pp.
- CEN (2003). Eurocode 8: Design of structures for earthquake resistance. European Standard, English version, Comité Européen de Normalisation (CEN), Brussels.
- Cornou, C., Cadet, H., Rocabado, V., Schmitz, M., Rendón, H., Causse, M. and Wathélet, M. (2010). Shear-wave velocities in Caracas inferred from inversion of phase velocities and ellipticities of Rayleigh waves. Revista de la Facultad de Ingeniería UCV, submitted.
- COVENIN (2001). Edificaciones sismorresistentes, COVENIN 1756:2001. Comisión Venezolana de Normas Industriales (COVENIN), FONDONORMA, MCT, MINFRA, FUNVISIS, Caracas.
- Delavaud, É. (2007). Simulation numérique de la propagation d'ondes en milieux géologiques complexes: application à l'évaluation de la réponse sismique du bassin de Caracas. PhD thesis, IPGP, France, pp. 155.
- Delaware (Seismographic Service Corporation of Delaware/ Tulsa, EEUU) (1950). Informe sobre investigaciones de aguas subterráneas del valle de Caracas. Unpublished, Instituto Nacional de Obras Sanitarias (INOS), (Ministerio de Obras Públicas), 189 pp.
- Feliziani, P., De Luca, P., Barrientos, C., Bastardo, S. and Ramírez, R. (1985). Estudio geotécnico del Área Metropolitana de Caracas (Sector Central). VI Congreso Geológico Venezolano.
- Feliziani, P., Piscitelli, G. and Castillo, A. (2004). Sistema de Información Geográfica aplicado al subsuelo del Área Metropolitana de Caracas – Proyecto SIGAMC. XVIII Seminario de Geotecnia, Caracas, 2004, Reports in CD.
- García, K., Morales, C., Sánchez, J. and Schmitz, M. (2006). Determinación de velocidades de ondas de corte ( $V_{s30}$ ) en el área metropolitana de Caracas, a partir de conversión SPT-velocidad de ondas de cortes, análisis de ondas superficiales y sísmica de refracción. VIII Congreso Venezolano de Sismología e Ingeniería Sísmica, Valencia, 2006, Reports in CD, 9 pp.
- Hernández, J.J. (2009a). Revisión de la sismicidad y modelo sismogénico para actualización de las evaluaciones de amenaza sísmica en la región norcentral de Venezuela. IX Congreso Venezolano de Sismología e Ingeniería Sísmica, Caracas, Reports in n CD, 15 pp.
- Hernández, J.J. (2009b). Confiabilidad sísmica-estructural de edificaciones existentes de Caracas. Proyecto Pensar en Venezuela, C.I.V., Jornadas 18 y 19 de septiembre de 2009, 107 pp.
- Hernández, J.J. and Schmitz, M. (2009). Evaluación actualizada de amenaza sísmica para la microzonificación de Caracas. V Coloquio sobre Microzonificación Sísmica, Caracas, 2009, Reports in CD, 4 pp.
- Hernández, J.J., Schmitz, M., Audemard, F. and Malavé, G. (2006). Marco conceptual del proyecto de microzonificación de Caracas y Barquisimeto. VIII Congreso Venezolano de Sismología e Ingeniería Sísmica, Valencia, Venezuela, 2006, Reports in CD, 8 pp.
- Hernández, J.J., Valleé, M., Feliziani, P., Schmitz, M., Oropeza, J., Tagliaferro, M., Castillo, A. and Cano, V. (2008). Peligro sísmico de deslizamientos en laderas de Caracas. 50 Aniversario de la Sociedad Venezolana de Geotecnia (SVDG), Caracas, 2008, Reports in n CD, 14 pp.
- Hernández, J.J., Schmitz, M., Delavaud, É., Cadet, H. and Domínguez, J. (2010). Espectros de respuesta sísmica en microzonas de Caracas considerando efectos de sitio 1D, 2D y 3D. Revista de la Facultad de Ingeniería UCV, submitted.
- Imai, T. and Yoshimura, M. (1970). Elastic Wave Velocity and Dynamics Characteristics of the Soft Ground. Soils and Foundation, Vol.18, No.1, pp.17-22.
- Kantak, P., Schmitz, M. and Audemard, F. (2005). Sediment thickness and a west-east geologic cross section in the Caracas Valley. Rev. de la Facultad de Ingeniería de la UCV, Vol. 20, No. 4, pp. 43-56.
- Morales, C., Masy, J., Schmitz, M., Cataldi, A., Rojas, H., Ávila, J., Rojas, S. and González, M. (2008). Aplicación de Métodos Geofísicos para la Caracterización de sitios en el estudio de Microzonificación Sísmica de Caracas. Conferencia 50 Aniversario de la Sociedad Venezolana de



- 
- Geotecnia (SVDG), Caracas, 2008, Reports in CD, 15 pp.
- Morales, C., Hernández, J.J., Schmitz, M., Cano, V. and Tagliaferro, M. (2010). Distribución de velocidades de ondas de corte en los primeros 30 m de profundidad ( $V_{s30}$ ), calibrados a partir de datos de relieve en la ciudad de Caracas. *Revista de la Facultad de Ingeniería UCV*, submitted.
- Murphy, V., Linehan, D. and Turcotte, T. (1969). Seismic Investigations, Valley of Caracas and the Litoral Central. Weston Geophysical Engineers International, Inc., Weston, Massachusetts (under planning and supervision of the Comisión Presidencial para el Estudio del Sismo), pp. 1-22.
- Newmark, N. (1965). Effects of earthquakes on dams and embankments. Fifth Rankine Lecture, *Géotechnique*, Vol. 15, No. 2, pp. 139-160.
- Ohta, Y. and Goto, N. (1978). Empirical Shear Wave Velocity Equations in Terms of Characteristic Soil Indexes, *Earthquake Engineering and Structural Dynamics*, Vol. 6, pp. 167-187.
- Papageorgiou, A.S. and Kim, J. (1991). Study of the propagation and amplification of seismic waves in Caracas valley with reference to the 29 July 1967 earthquake: SH waves. *Bulletin of Seismological Society of America*, Vol. 81, pp. 2214-2233.
- PEER (2005). PEER NGA Database. Pacific Earthquake Engineering Research Center (PEER), California.
- Pitilakis, K. (2004). Site effects. Chapter 5 in *Recent advances in earthquake geotechnical engineering and microzonation*, Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Rocabado, V., Schmitz, M., Rendón, H., Vilotte, J.-P., Audemard, F., Sobiesiak, M., Ampuero, J.-P. and Alvarado, L. (2006). Modelado numérico de la respuesta sísmica 2D del valle de Caracas. *Revista de la Facultad de Ingeniería de la UCV*, Vol. 21, No. 4, pp. 81-93.
- Rocabado, V., Schmitz, M., Hernández, J.J. and Morales, C. (2010). Relación entre período del suelo y profundidad de los sedimentos para la ciudad de Caracas. *Revista de la Facultad de Ingeniería UCV*, submitted.
- Sánchez, J., Schmitz, M. and Cano, V. (2005). Mediciones sísmicas profundas en Caracas para la determinación del espesor de sedimentos y velocidades sísmicas. *Boletín Técnico del IMME*, Vol. 43, No. 2, pp. 49-67.
- Schmitz, M., Enomoto, T., Ampuero, J.-P., Rocabado, V., Kantak, P., Sánchez, J., Rendón, H., González, J., Abeki, N., Villotte, J.-P., Navarro, M. and Delgado, J. (2002). Seismic microzoning study in Chacao district, Caracas, Venezuela. 12<sup>th</sup> Europ. Conf. on Earthq. Eng., London, 2002, Paper Ref. 808, 10 pp.
- Schnabel, P., Lysmer, J. and Seed, H. (1972). SHAKE - A computer program for earthquake response analysis of horizontally layered sites, *Earthquake Engineering Research Center*, Report No. UCB/EERC-72/12. University of California, Berkeley.
- Seed, H.B., Idriss, I.M. and Dezfulian, H. (1970). Relationships between soil conditions and building damage in the Caracas earthquake of July 29, 1967. *EERC-Report 70-2*, Berkeley, California 40 pp.
- Semblat, J.F., Duval, A.M. and Dangla, P. (2002). Seismic site effects in a deep alluvial basin: numerical analysis by the boundary element method. *Computers and Geotechnics*, Vol. 29, pp. 573-585.
- Singer, A., Zambrano, A., Oropeza, J. and Tagliaferro, M. (2007). Cartografía de las unidades geológicas cuaternarias del Valle de Caracas a escala 1:25.000. IX Congreso Geológico Venezolano, Caracas, 2007, Reports.
- Suárez, G. and Nábělek, J. (1990). The 1967 Caracas earthquake: Fault geometry, direction of rupture propagation, and seismotectonic implications. *J. Geophys. Res.*, Vol. 95, pp. 17459-17474.
- Urbani, F. and Rodríguez, J. (2004). Atlas geológico de la cordillera de la costa de Venezuela. Caracas, junio 2004. Ediciones Fundación GEOS, escala 1:25.000 pp. 146.
- Wald, D. and Allen, T. (2007). Topographic slope as a proxy for seismic site conditions and amplification: *Bulletin of Seismological Society of America*, Vol. 97, No. 5, pp. 1379-1395.
- Whitman, R.V. (1969). Efecto de las condiciones del suelo en el daño producido a las estructuras por el terremoto de Caracas del 29 de Julio de 1967. Study executed for the Comisión Presidencial para el Estudio del Sismo.

**5th International Conference on Earthquake Geotechnical Engineering**

January 2011, 10-13

Santiago, Chile

---

Yamazaki, Y., Audemard, F., Altez, R., Hernández, J., Orihuela, N., Safina, S., Schmitz, M., Tanaka, I., Kagawa H. and the JICA Study Team - Earthquake Disaster Group (2005). Estimation of the seismic intensity in Caracas during the 1812 earthquake using seismic microzonation methodology. Revista Geográfica Venezolana, Número Especial 2005, pp. 199-216.